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(71) Applicant:
Scientific Drilling International
Houston, Texas 77073 (US)

(72) Inventors:
- **Van Steenwyk, Donald M.**
  San Marino, CA 91108 (US)
- **Towle, James N.**
  Seattle, WA 98103 (US)
- **Price, Timothy**
  Camarillo, CA 93012 (US)

(74) Representative:
Pellmann, Hans-Bernd, Dipl.-Ing. et al
Patentanwaltsbüro
Tiedtke-Bühling-Kinne & Partner
Bavariaring 4-6
80336 München (DE)

(54) **Combined electric-field telemetry and formation evaluation method and apparatus**

(57) An apparatus for borehole electric-field telemetry that comprises a source of modulated voltage or current, at least one axially non-conductive collar connected between pipe sections in a pipe string, and a system of insulated wireline components providing electrical connections, insulated from drilling fluids, between the ends of the one or more aforementioned insulated collars in the pipe string, to transmit the voltage or current.

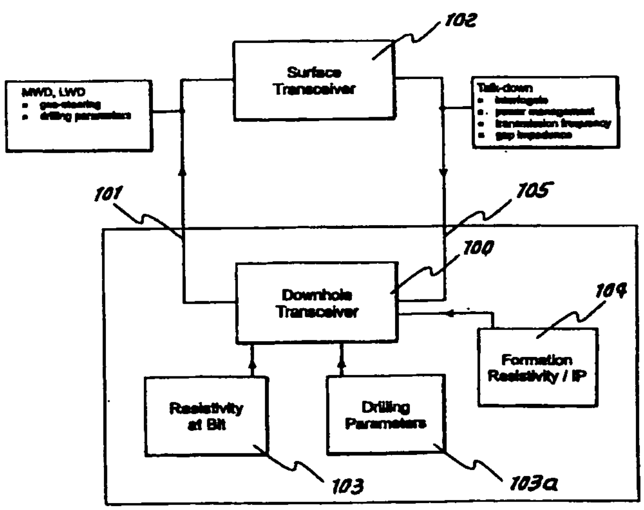

FIG. 1a.

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embodiment, will be more fully understood from the following specification and drawings, in which:

DRAWING DESCRIPTION

[0012]

Fig. 1a shows elements of the invention in block diagram form;
Fig. 1b is a section showing details of the apparatus incorporating the invention, the downhole portions of the invention being shown to an enlarged scale;
Figs. 2a, 2b and 2c show the basic components of the invention in three possible configurations; Fig. 2a shows the invention configured with a single insulating gap; Fig. 2b shows the invention configured with the gap positioned uphole of a high resistivity rock layer; Fig. 2c shows the invention configured with two gaps;
Fig. 3 shows an equivalent circuit diagram of the transmission path used by the invention for downhole telemetry and formation evaluation;
Fig. 4 shows details of the bottom hole assembly for a two-gap configuration of the invention;
Fig. 5 shows the invention configured for azimuthal resistivity-at-bit measurements;
Fig. 6 shows the invention configured for formation resistivity and induced polarization response measurements above a motor that drives a drill bit;
Fig. 7 shows the invention configured for azimuthal resistivity and induced polarization evaluation in the formation adjacent to the borehole;
Fig. 8 is a more detailed view showing components in a drillstring;
Fig. 9 is a section showing details of switching and sensor modules;
Fig. 10 is a block diagram;
Fig. 11 is a section showing adaptation to use with well casing;
Fig. 12 is a section showing use of multiple wirelines;
Fig. 13 shows details of insulative gap construction;
Fig. 14 shows use of a well fluid pressure responsive switch;
Fig. 15 shows use of multiple receiver electrodes;
Fig. 16 shows target detection by means of the invention;
Fig. 17 is another schematic elevation showing apparatus in a pipe string incorporating the invention; and
Fig. 18 is a schematic showing of the use of multiple surface electrodes.

DETAILED DESCRIPTION

[0013] The mechanical limitations imposed by the prior art of toroidal coupled borehole telemetry systems, and the difficulties in matching the drilistring-formation impedance of a short-gap, direct-coupled system are addressed by the present invention. By providing insulated drill collars or gap sub-assemblies used in conjunction with electric current supplying components and circuits, the invention provides direct coupled impedance matching, optimum location of the transmission gap in complex geologic systems, and the integration of formation evaluation geo-steering, and downhole telemetry, in a single system.

[0014] In certain embodiments of the invention, a direct coupled impedance match, or near match, to the drilistring-formation transmission path is provided. By proper selection of one or more insulated drill collars or gap sub-assemblies and conventional drill collars, the drillstring is configured to present an electrical impedance match between the downhole electric-field telemetry system and the surrounding formation. An insulated wireline may connect upper and lower sub-assemblies for completing an electrical circuit comprised of the upper drillstring, power source, wireline, bottom hole assembly, and formation.

[0015] A block diagram of the invention is shown in Fig. 1a. A downhole transceiver **100** transmits at **101** either drilling parameters or the results of formation evaluation measurements to a transceiver **102** at the surface, or receives signals from a surface transmitter for power management or other control requirements. Note transducers or sensors **103**, **103a**, and **104** supplying data to the transreceiver. The same instrumentation is used for both downhole telemetry and evaluation of formation resistivity and induced polarization (IP) response. Note transmission line **105** from **102** to **100**.

[0016] Fig. 1b shows the invention in a measurement- while-drilling (MWD) application. A bent sub-assembly means **302** in the drillstring provides directional control for the drilling operations. Voltage application apparatus is shown in the string and includes battery **24**, insulated wireline **305**, connected at connections **314** and **315** to upper and lower instrument housings **311** and **312**, which house components, such as batteries, sensors and switching apparatus. Voltage or current is applied by electrical contact means **306** and **304** to the drilistring, and then to the formation. A borehole drill motor **313** is shown in the string above the drill bit **316**. Upper extent of the string is indicated at **22**, and the borehole appears at **22a**, in formation **22b**. A circuitry housing appears at **307**. Surface equipment appears at **22c**.

[0017] Figs. 2a, 2b and 2c illustrate three possible configurations of the system used as a means of downhole electric-field telemetry. In each configuration, a voltage is impressed across an insulated drill collar **1**, between upper and lower steel drillstring sections **4** and **5**, and drives an electric current through the earth **2**. In configuration of Fig. 2a, a power source **3** is connected across an upper section **4** of the drilistring, and a lower section **5** of the drillstring, as by wireline components **6** and a signal source (modulator) indicated as a switch **7**,

to downhole telemetry, the invention provides a means for evaluation of resistivity and induced polarization (IP) response at the bit, in the formation surrounding the drilistring or in the formation surrounding a cased borehole. By generating an electric field in the surrounding medium, i.e., formation, and with multiple current or voltage-sensing electrodes placed on the drilistring, at the bit, or on the casing of a cased borehole, the resistivity and IP response of the surrounding medium can be measured.

[0026] To evaluate formation resistivity and IP response at and directly ahead of the bit, a voltage pulse waveform, or a set of selected frequencies, is applied across an impedance matched insulated gap or gaps in the drillstring and drill collars configured as shown in Fig. 5. The bulk resistivity of the formation surrounding the insulated gap, drill collar or motor, bit-box, and bit can then be determined by well known data reduction methods for geophysical interpretation of formation resistivity and IP response. The resistivity at the bit is analytically separated from the bulk resistivity surrounding the bottom hole assembly by noting that, as the bottom hole assembly passes through a formation and the resistivity is measured, changes in the bulk resistivity will be due to resistivity changes at the bit.

[0027] Referring to the schematic showing of Fig. 5, an upper power and control sub-assembly **36** having one or more current **37** and guard **38** electrodes is mounted on or in and insulated from the drilistring **39**. This sub-assembly also carries a power source **40** and control and switching electronics **41**. See also driver **41a** for switch arm **41**. An insulated tubular drill collar or gap sub-assembly **42** separates the upper power and control sub-assembly from the motor housing or lower metallic drill collars **43**.

[0028] A resistivity-at-bit lower sub-assembly capable of azimuthal measurements is housed by a tubular mandrel **44** extending downwardly from the motor **43**. This mandrel carries an instrumentation package directly above the bit **45**. The instrument package comprises a set of one or more guarded or unguarded current electrodes **46** mounted on and insulated from the mandrel or drill collar; and a means **48a** is provided for connecting lower extent of the wireline **48** to the current electrodes **46** individually, or in combination, at each level. Each electrode is shown as surrounded by an insulated guard electrode **47** and associated electronics to provide focusing and to reduce return currents along the motor housing or drill collar. Accordingly, electrical field "lines" can be established at different azimuth locations about the string axis.

[0029] Multiple voltage sensing electrodes **49** are mounted on insulated pads **50** on the mandrel. The potential difference between the various voltage sensors is selected from the upper control sub-assembly via wireline connections **48** from the upper sub-assembly electrodes to the bit box electrodes through the drill collars and/or motor housing. Fig. 5 also represents the combined use of MWD (measure while drilling) technique, together with one of multiple electrodes, as referred to, to measure formation properties. Measured voltage or current values are either interpreted as formation resistivity or IP at control sub-assembly for transmission to the surface by the methods described in the previous paragraph, or the values themselves are transmitted to the surface for interpretation. In this case, the results of formation evaluation are equivalent to sensor output.

[0030] By proper configuration of insulated drill collars or gap sub-assemblies, electrodes, and wireline connections, a unique borehole application of the surface geophysical dipole-dipole resistivity technique is possible. Fig. 6 schematically illustrates this configuration. Other similar configurations are possible corresponding to the various electrode configurations developed for (surface) resistivity and IP measurements. Using this configuration, one or more gap subassemblies and wireline system components are used to provide formation resistivity measurements at distances from the borehole previously unobtainable by the prior art.

[0031] In Fig. 6, a series of insulated, tubular drill collars or gap sub-assemblies **57**, and electrically conducting drill collars or sections of drillstring **58** and **59** are connected in a dipole-dipole configuration, in accordance with known surface geophysics. A voltage is applied via source **82** by conductor means **80** and connection means **58a** and **58b** across conducting sections **58** and **59**, which act as effective current electrodes. Electric current **84** is thereby driven from the conducting sections into the formation **85** surrounding the borehole **85a**. Receiver means **83** is electrically connected to conducting sections **60** and **61** by conductor means **81**, and connection means **60a** and **60b**, and the receiver means detects the potential difference between such conducting sections, which act as effective potential electrodes. By interpretive means known in the art of surface geophysics, the electrical resistivity of the formation surrounding the borehole can be determined from such receiver measurements and knowledge of the voltage at source **82**.

[0032] In Fig. 7, the apparatus is configured so as to provide measurement of variable azimuthal resistivity in the formation adjacent to the drillstring. A power source at **68a** and suitably driven switching circuits at **67** and **71** drive current along paths **77** into and in the formations, through electrodes **65** and **73**, located around the circumference of upper and lower sub-assemblies **64** and **72**, mounted between upper and lower sections of the drillstring **63** and **63a**, and connected to the power source by an insulated wireline **70**. An insulated, intermediate section of the string appears at **69**.

[0033] A downhole motor appears above the drill bit **75** at **76**. The current flow at electrodes **65** and **73** may be focused by guard electrodes at **74** and **66**. Switches **67** and **71** operate to azimuthally distribute the voltage

ments **408**. By appropriate selection of elements **411** to provide connection or non-connection of the conductors to the electrically conductive drilistring elements, the non-conducting sub-assemblies are connected in series, parallel or any combination thereof with the power source.

[0044] As in previously described forms of the invention, a modulator **414** is deployed in the bottom hole assembly **415** so as to modulate the flow of electric current in the aforementioned circuit for the purpose of transmission of signals derived from one or more sensors **416**.

[0045] Referring to Fig. 13, elements of the apparatus are shown in more detail, in association with a drilistring in a well. The string includes drill pipe sections, with sections **104** extending from the earth surface in a borehole **120**, to connect at **121** to conductive adapter **435** at the upper end of insulating portion **432** of a non-conductive collar.

[0046] The gap sub-assembly may be provided with a resistive element **431** providing a leakage path for wireline communication with the bottom hole assembly. The resistive element **431** is embedded in the insulative material **432** of the gap sub-assembly and electrically connected to upper **435** and lower **436** conductive fittings at **433** and **434**, respectively. Communication from the surface to the sensor and modulator electronics is accomplished by a communications path employing wireline means **437** connected through upper battery pack **439**, to insulated wireline **440,** to downhole modulator and sensor electronics **442**.

[0047] In another form of the invention, the insulated wireline components are replaced by a conductor **440** within an insulating tubular sheath **441**, as shown in Fig. **12**.

[0048] Pressure changes or flow of drilling fluid may be encoded for communication from the surface to downhole components of the invention. Fig. 14 shows the use of a pressure switch **701** for this purpose. Changes in pressure or flow rate of drilling fluid **702** internal to drillstring **703** is sensed by pressure switch means **701**, which in turn provides input signals to control means **704**. Control means **704** is used to control operation of downhole instrumentation, including modulator means **705**, power source **706**, and sensor means **707**. Typically changes in the drilling fluid flow rate, controlled from the surface, can be used to conserve downhole power consumption by the means of the invention.

[0049] In another form of the invention, multiple receiver electrodes **501**, **502**, **503**, **504**, and **505** are deployed as shown in Fig. 15. Some of the electrodes may be effected by direct connections **501a** and **505a**, to the active drilistring or casing **501**, or adjacent well casings **505**. By a switching means **506** and comparator means **507**, electrode signals are combined in a manner which provides the best signal reception from a downhole transmitter. The switching and comparator means may also be used to provide information on lateral changes in geologic formation, such as the change in resistivity from formation **508** to formation **509**.

[0050] The invention improves methods of downhole target detection, location, and tracking while drilling as by means shown in Fig. 16. A time-varying current **521** is injected along the drillstring and into the formation surrounding the drillstring by transmitter means **522**. Target casing **523** provides an electrically conductive path in the formation for currents **521**. As a result, current is concentrated, **524**, on target casing **523**. Current flow **524** results in a time varying magnetic field **525**, which is measured by magnetetometer means **526**. Time varying magnetic fields **525**, measured by means **526** in the bottom hole assembly, bears a known relation to the position of target casing **523**. Such measurements are transmitted to the surface for reception by receiver means **9** and calculation of target position by surface means **528**.

[0051] The invention also incorporates several additional improvements over the prior art. These are:

1) A means for the generation of low voltage electrical pulses to carry the signal information and thereby reduce the danger of electrical breakdown and discharge in the wellbore. In the prior art of direct coupled systems, the impedance mismatch between the source and surrounding formation was sometimes overcome by generating extremely high voltage pulses by the charging of a downhole capacitor. By reducing the required voltage, the present novel configuration reduces the hazard of such wellbore discharges.

2) The generation of easily controlled and synthesized low voltage pulse waveforms also permits the application of recent advances in digital signal processing to the detection of low-level signals in the presence of natural and man-made noise.

3) The improved detection of synthesized waveforms permits Wavelet signal processing for the interpretation of low level signals. Wavelet analysis is a relatively new method of signal processing, which permits efficient "de-noising" of broad-band signals (see Daubechies, I, 1992, "Ten Lectures on Wavelets", Society for Industrial and Applied Mathematics). The received waveform of a doublet (positive-negative pulse pair) when transmitted through the drillstring-formation path is modified so as to resemble one of the Daubechnies family of wavelets. This permits the compact and therefore fast recognition of electric field signals in the presence of noise.

4) Detecting the arrival time of electric field pulses generated at the downhole gap sub-assembly permits interpretation of pulse waveforms in the time domain, thus allowing determination of distance to discontinuities in formation resistivity.

5) Improved detection by employing multiple voltage-sensing electrodes on the surface and using

object, such as a nearby well casing.

14) The apparatus and methods may be used to locate the position and orientation of a nearby electrically conductive object, such as a well casing. See the casing **300** in Figs. 1, 4 and 7, the presence of which affects the return current flow in the formation, to be detected as by voltage variation detector at **8** at the surface (see Fig. 2). Also, wavelet signal processing may be used to detect anomalous magnetic or electric-fields. The frequency of a periodic source voltage at the insulated gap may be varied to obtain maximum electric or magnetic field response from the conductive target.

15) The electrical and induced potential structure of the formation surrounding the borehole and of the formation between the surface and downhole locations can be determined with the apparatus of the invention by measuring the potential between various of the multiple surface electrodes of the apparatus in response to a known current or voltage waveform transmitted by the downhole source apparatus, either expressly for the purpose of determining the geoelectrical structure or in association with telemetry transmissions.

Conversely, the apparatus can be used to evaluate the electrical and induced potential structure of the formation surrounding the borehole and of the formation between the surface and downhole locations by comparison of voltage received at various downhole locations in response to known voltage or current waveforms generated between various configurations of surface electrodes.

16) An apparatus and method for downhole magnetometric formation evaluation. By addition of appropriate magnetic field sensors to the bottom hole assembly, time varying magnetic fields produced by the concentrated flow of electric current in electrically conductive regions of the formation can be detected. Using the prior art of surface geophysics, the electrical structure of the formation surrounding the borehole is determined.

[0052] Various uses of the invention are listed as follows:

1. Use of the bottom hole assembly below a non-conducting drill collar, as an electrode for transmission of electric currents in an electric-field borehole telemetry system, the non-conducting drill collar providing an insulating gap for transmission of electric currents to the surface.
2. Use of centralizers as electrical contactors between components of an electric-field telemetry system mounted in a drillstring and the drillstring itself, the bow springs of the centralizers making contact with the interior wall of the drillstring.
3. Use of drillstring stabilizers as electrical contactors between drillstring components and the borehole wall in an electric-field telemetry system, the stabilizer blades making electrical contact with the borehole wall.
4. Use of drill collars comprised of electrically insulating material to provide electrical gaps in the drillstring, said gaps being sufficiently longer than in the prior art, for the purpose of reducing downhole power requirements in an electric-field downhole telemetry system.
5. Use of one or more electrically insulating drilistring collars in an electrically conductive drillstring, together with one or more electrically insulated sections of wellbore casing, the ends of the insulating drillstring collars electrically connected by insulated wireline components and the insulated sections of wellbore casing located, so as to maximize the flow of electric current to the surface in an electric-field downhole telemetry system.
6. Use of one or more electrically insulating drillstring collars, the ends of the insulating collars connected by electrically insulated wireline components in a manner such that the impedance of the entire assembly, measured from the surface of the earth, is varied so as to comprise a borehole telemetry system.
7. Use of a downhole pressure switch in an electric-field telemetry system to detect acoustic pulses, transmitted from the surface, to control operation of the electric-field telemetry system.

[0053] Fig. 17 is a schematic showing a pipe string 299 having multiple insulated, sub-surface pipe string sections 301-304, across which instrumentation or circuitry 305 and 306 in upper and lower housings 307 and 308 is connected. See connection 309 from circuitry or instrumentation 305 in upper housing 307 to the bore of string section 301; and see connection 311 from circuitry or instrumentation 306 in lower housing 308 to the bore of string section 304. Additional connections are shown at 313, 314 and 315 from circuitry 310 to the string sections 302 to 304. Wirelines are indicated at 320-323. Such instrumentation may include batteries, pulse producing means, and circuitry such as amplifiers, and pulse wave shaping equipment, encoding equipment, and frequency and phase shifting means.

[0054] Fig. 18 shows multiple electrodes, including surface electrodes 330 and 331 spaced at distances d_1 and d_2 from the top of the sub-surface pipe string 333. The latter is representative of any of the pipe strings described above and shown in any of Figs. 1-16, containing apparatus as described above and shown in any of Figs. 1-16. Such electrodes are typically on or under the ground surface, and adapted to sense changes in electromagnetic fields including electrical fields transmitted in the underground formation and in the pipe string, to the surface, by operation of the down-hole equipment including pulse producing apparatus; and such electrodes and/or the pipe string are also adapted

face electrodes are surface transmitter electrodes connected in a configuration to optimize signal transmission downwardly to a downhole signal receiver, via a signal transmission path, a portion of which includes the underground formation, and said receiver is carried in the pipe string in a borehole and receiving said signal via said path.

10. The apparatus of claim 9 further comprising inborehole electronic circuitry, and mechanical means controlled by said signal transmission received by the receiver.

11. The apparatus of claim 1 further including multiple conductive sections which together with said insulative collar or collars provide effective enhancement of electrical resistance between said electrical connections.

12. The apparatus of claim 9 wherein direct electrical connection of the receiver to the casing of a well is employed.

13. A method for the measurement of underground formation resistivity and/or induced polarization that includes providing spaced electrical connections to a pipe string in the formation, applying an electric signal such as voltage between said connections, and measuring resultant changes in voltage between spaced locations in the formation into which the pipe string extends, said measuring including providing spaced electrodes selectively positioned at the earth's surface, and operating said electrodes to optimally detect changes in an electronic filed or fields established by said signal application to said connections.

14. The method of claim 13 wherein the pipe string is provided to comprise a casing string.

15. The method of claim 13 further including:

a) providing upper and lower housings with associated sub-assemblies comprising current electrodes and potential electrode pairs spaced azimuthally about the circumference of an electrically conductive drillstring sub-assembly,
b) providing a means to insulate said current and potential electrodes from said drilistring sub-assembly,
c) providing one or more electrically insulating drilistring sub-assemblies, the housings separated by lengthwise extent of at least one of said insulating drilistring sub-assemblies,
d) providing one or more electrically conductive drilistring elements,
e) providing a means to electrically connect selected electrodes of said upper and lower sub-assemblies separated by one or more said conductive and insulating drillstring elements to a source of voltage or current,
f) and measuring the voltage across and current between selected electrode pairs, in conjunction with said positioning of said spaced electrodes at the earth's surface.

16. The method of claim 13 further comprising the step of resolving the azimuthal direction of resistivity or induced polarization.

17. The method of claim 13 further comprising detecting and locating an electrically conductive target or geologic structure nearby the pipe string such as a nearby well casing, and including injecting electric current into the formation surrounding the wellbore and target, and detecting anomalous vector magnetic fields produced by the concentration of the aforementioned electric current on the target.

18. The method of claim 13 wherein said electrical signal is one of the following:

i) pulsed voltage
ii) pulsed current
iii) amplitude modulated voltage
iv) amplitude modulated current
v) frequency modulation of one of:

x_1) voltage
x_2) current

vi) phase shifting of one of

x_1) voltage
x_2) current

vii) polarity reversal signal.

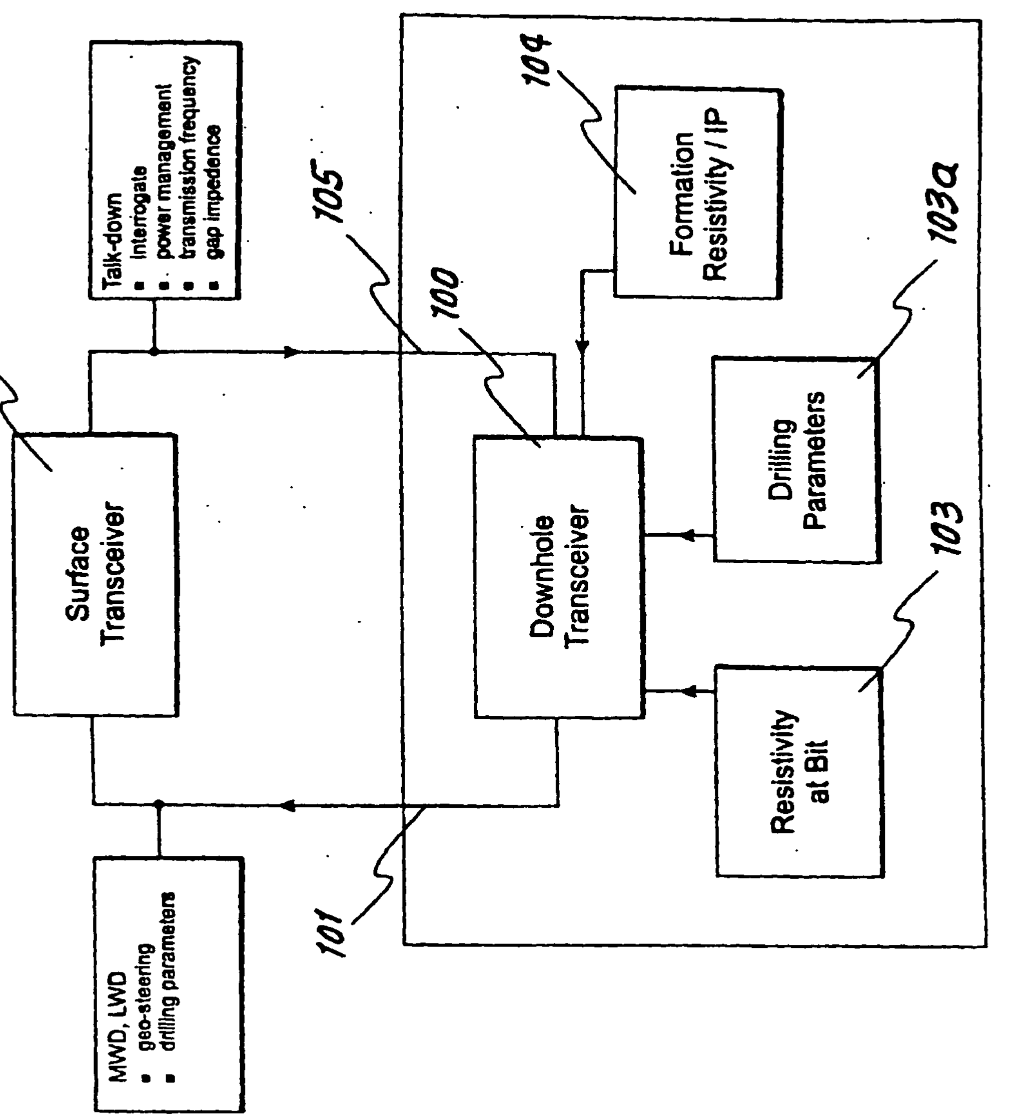
19. The method of claim 13 wherein said signal is produced as a pulse to thereby provide an approximate electrical impedance match between:

i) circuitry defined by said connections, said upper, and lower extents of the drilistring, and said insulative sections of the pipe string,
ii) and the underground formation surrounding said circuitry.

20. The method of claims 13 further comprising logging an underground formation, employing a pipe string extending in a borehole in the formation, and which includes

a) applying said signal to electrically conductive portions of the string that are separated by

FIG. 1a.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Surface Transceiver
Talk-down
interrogate
power management
transmission frequency
gap impedence
105
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Downhole Transceiver
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Formation Resistivity / IP
103a
Drilling Parameters
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Resistivity at Bit
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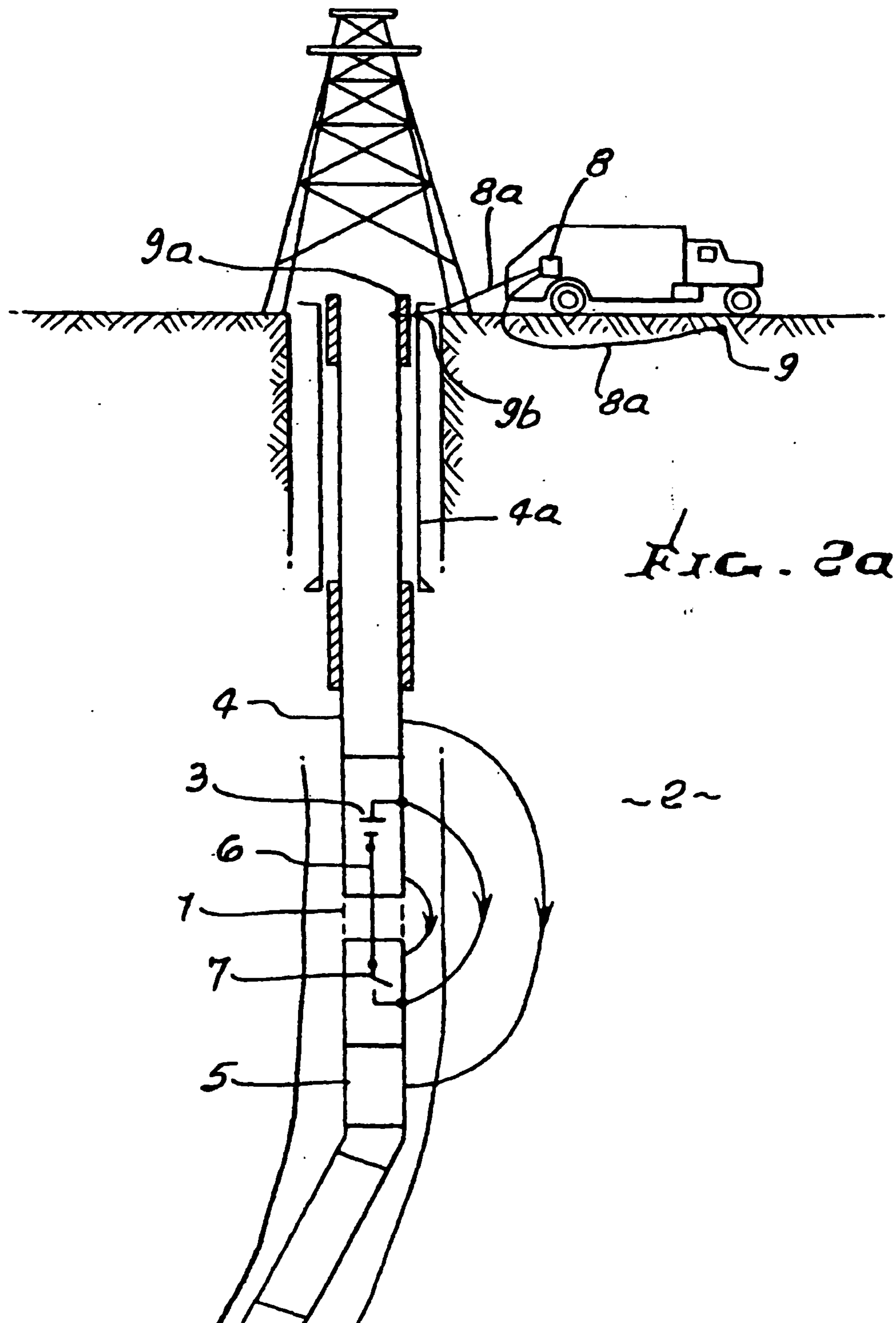


FIG. 2a.

FIG. 2C.

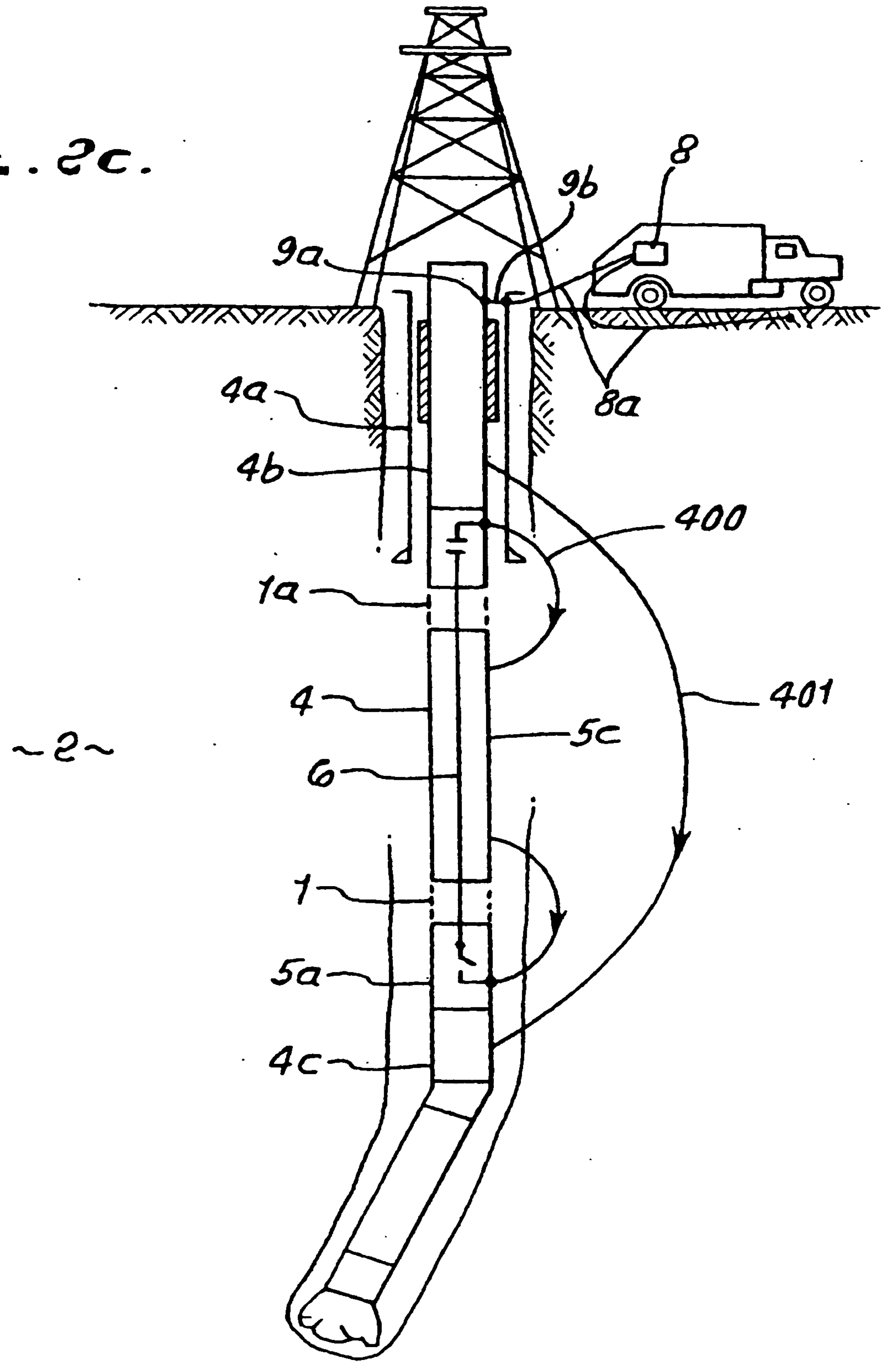


FIG. 4.

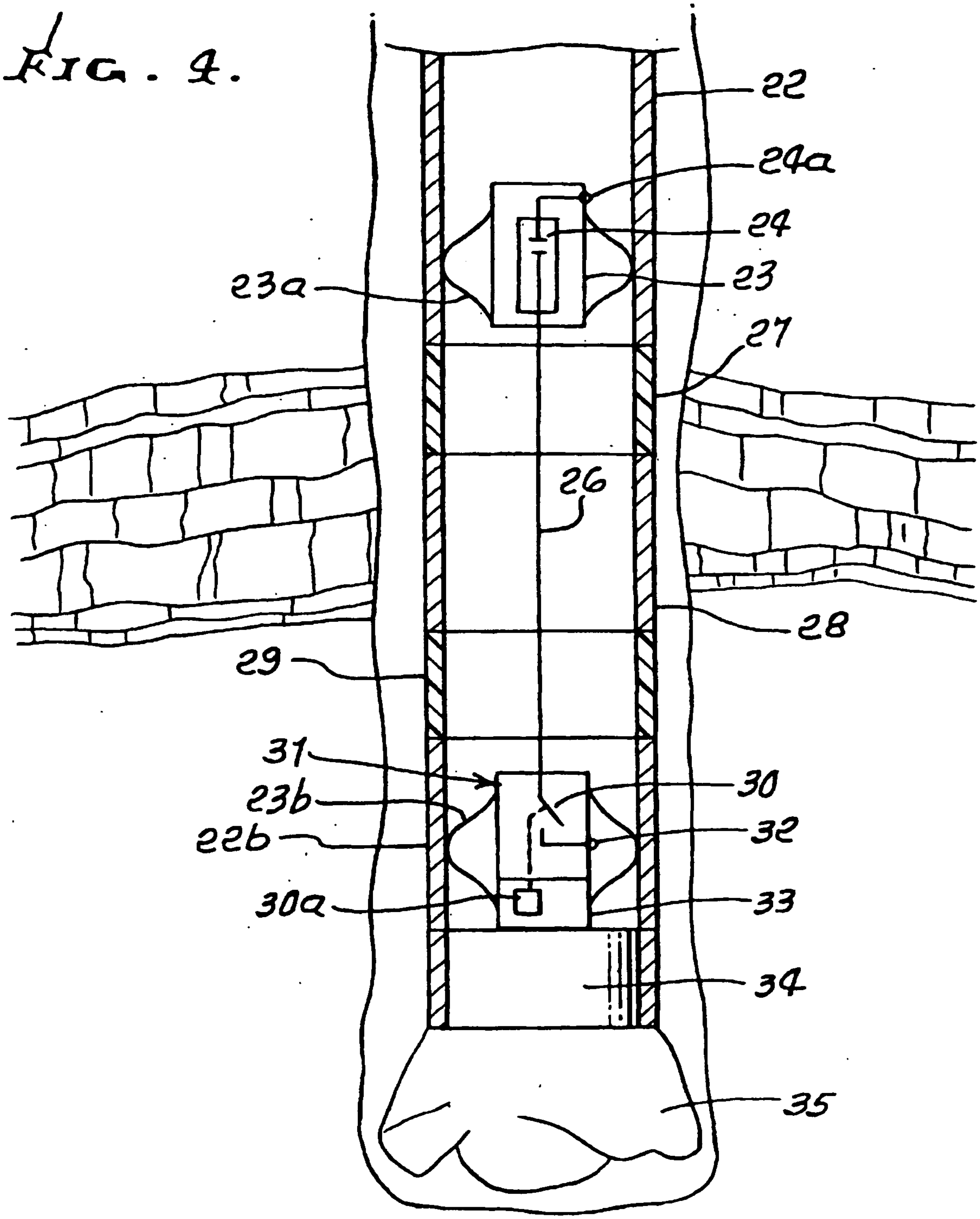
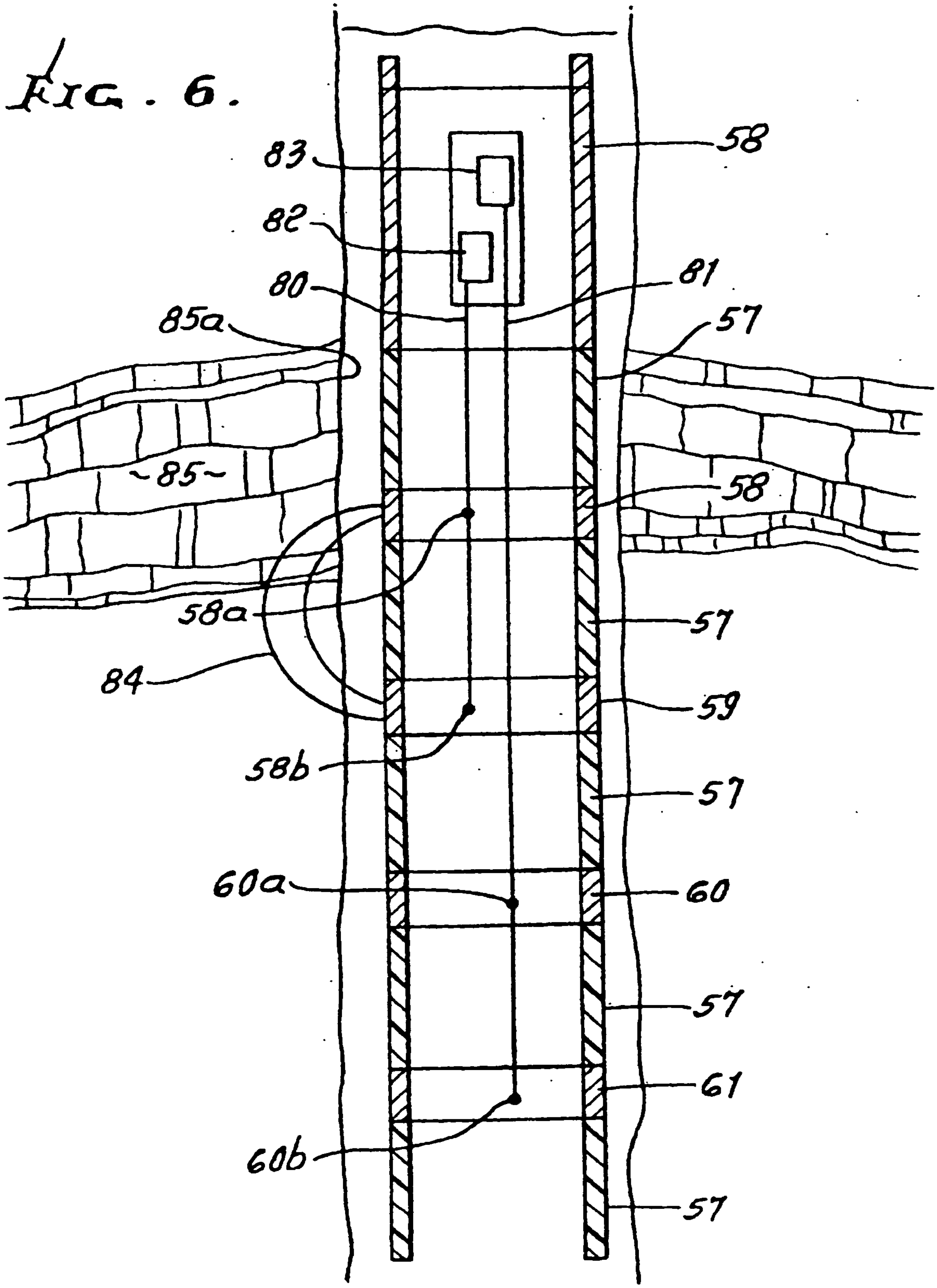


FIG. 6.



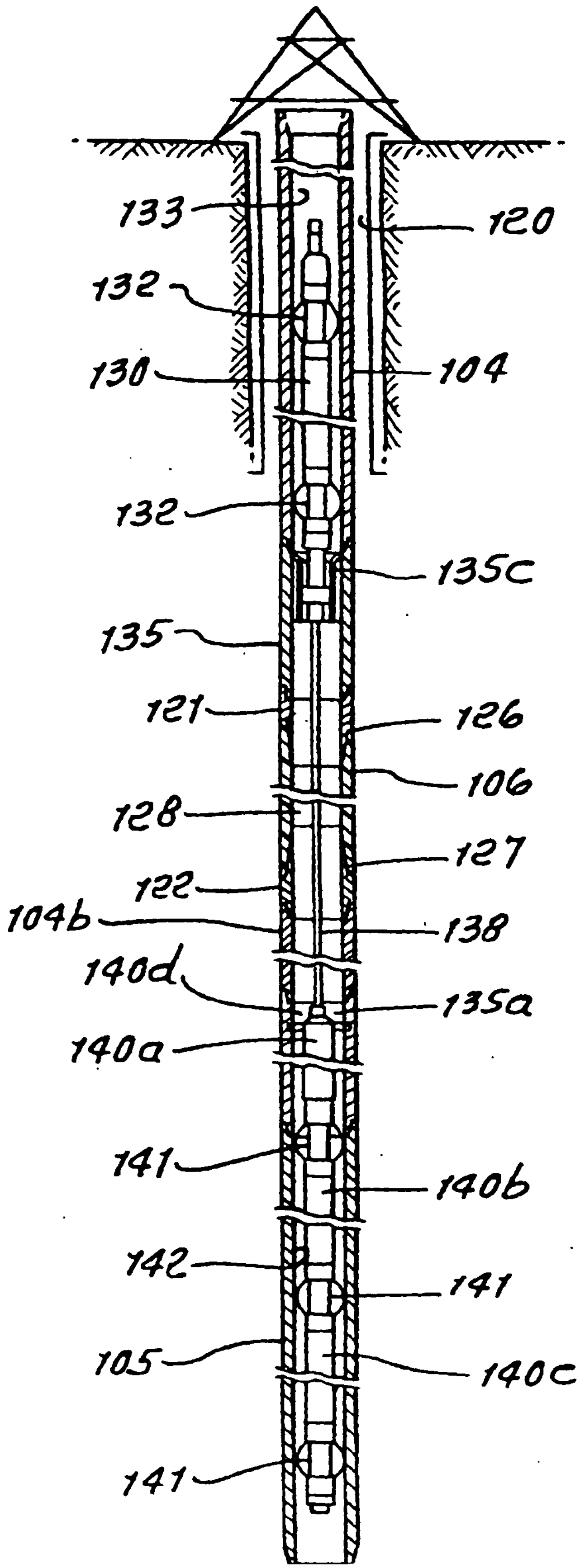

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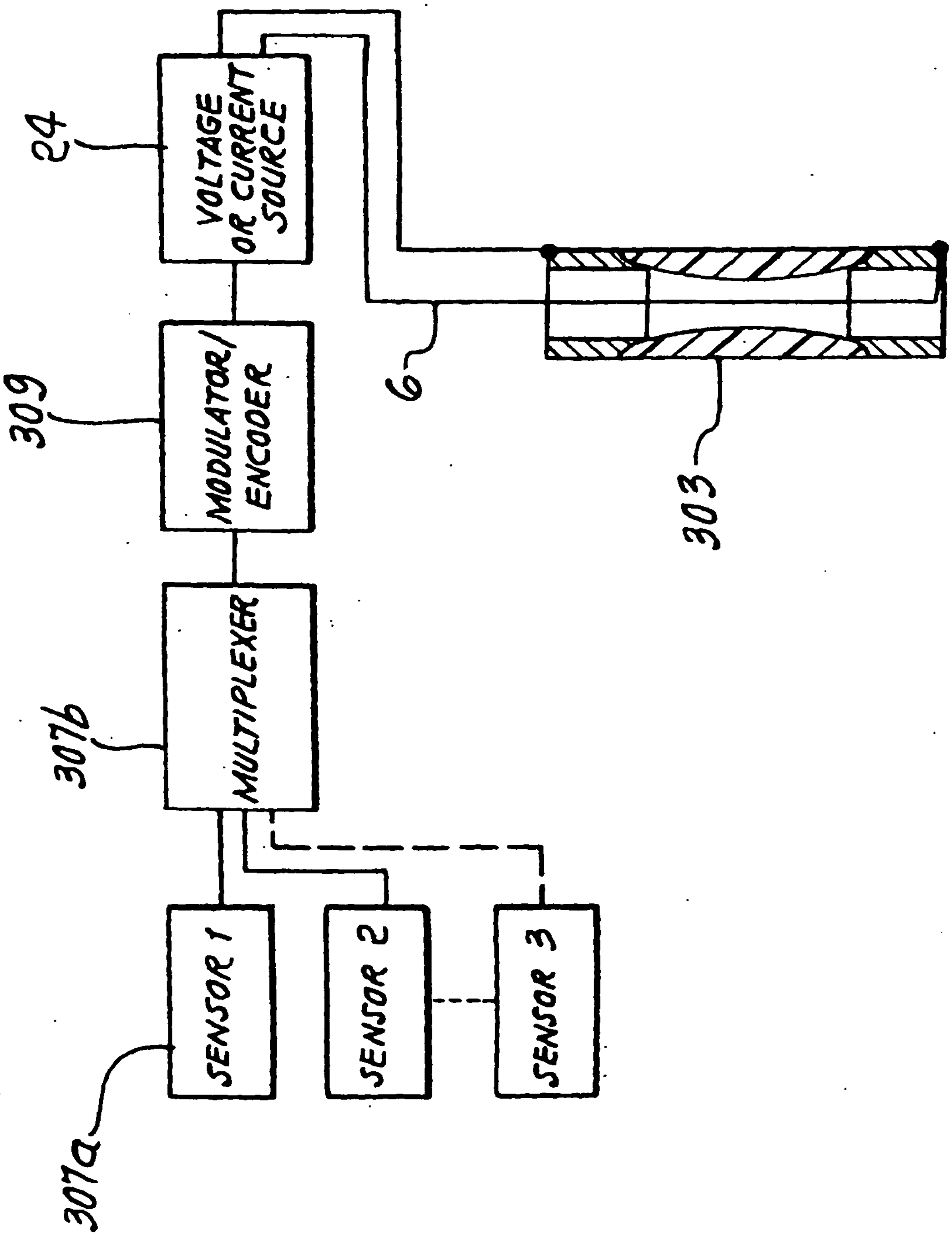
FIG. 8.

FIG. 10.


24
VOLTAGE OR CURRENT SOURCE
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SENSOR 2
SENSOR 3
307a

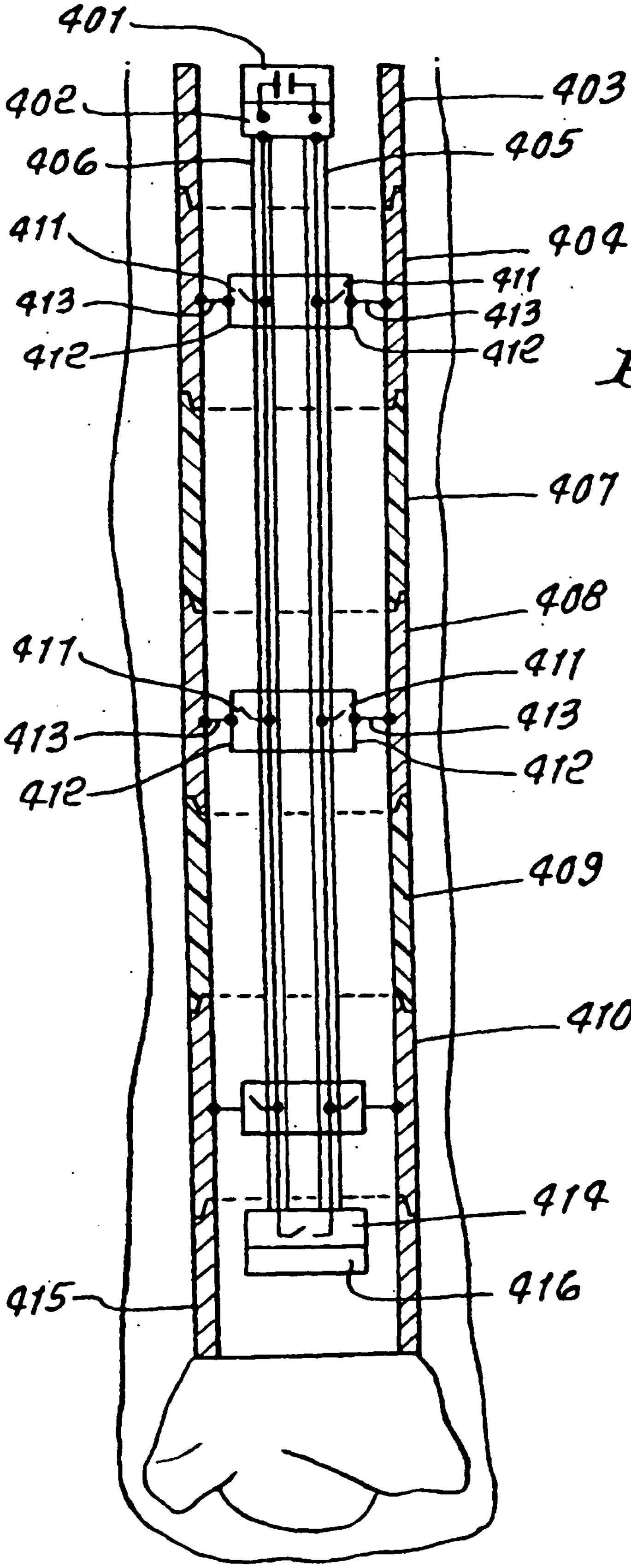
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FIG. 12.

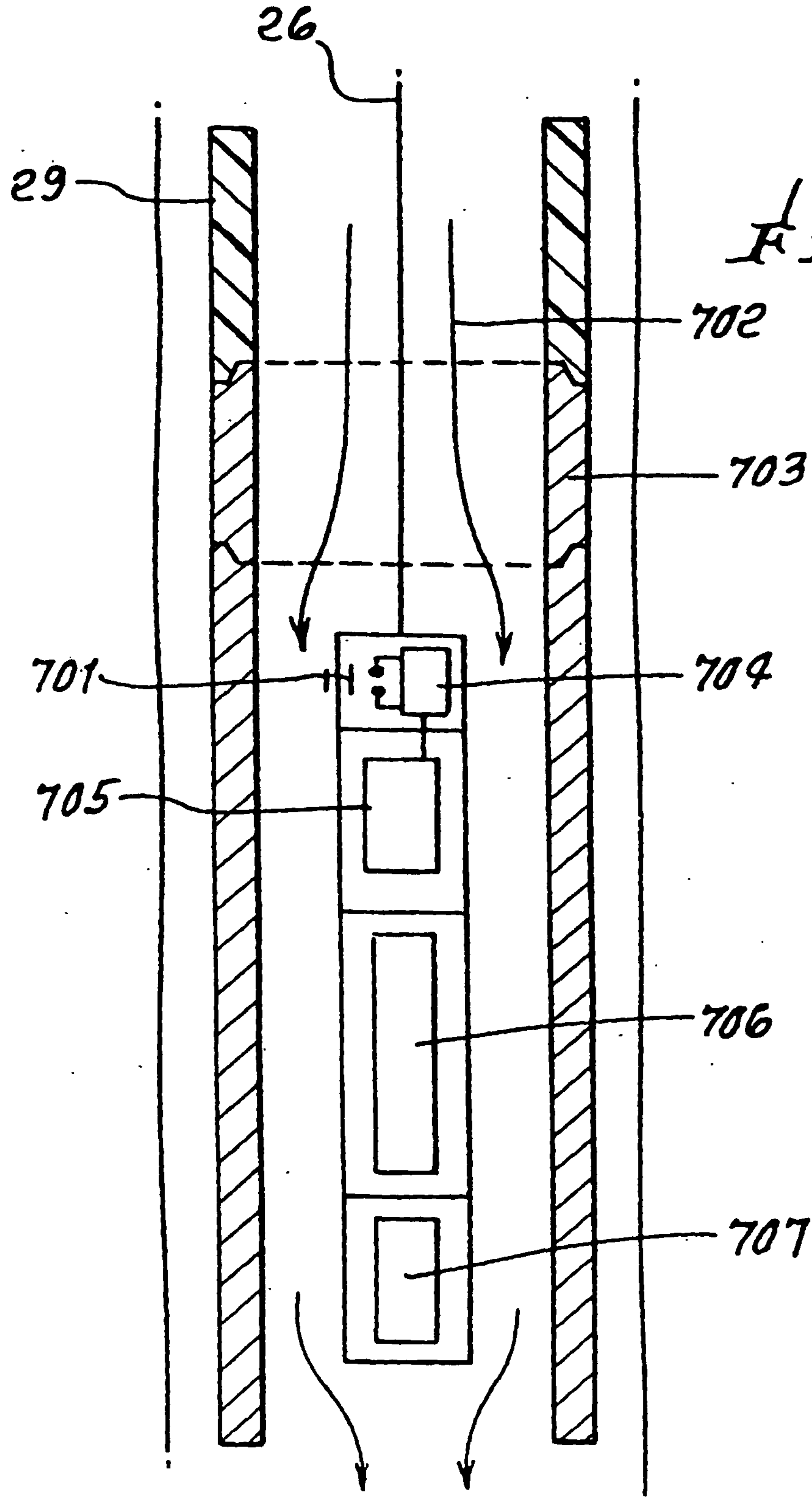
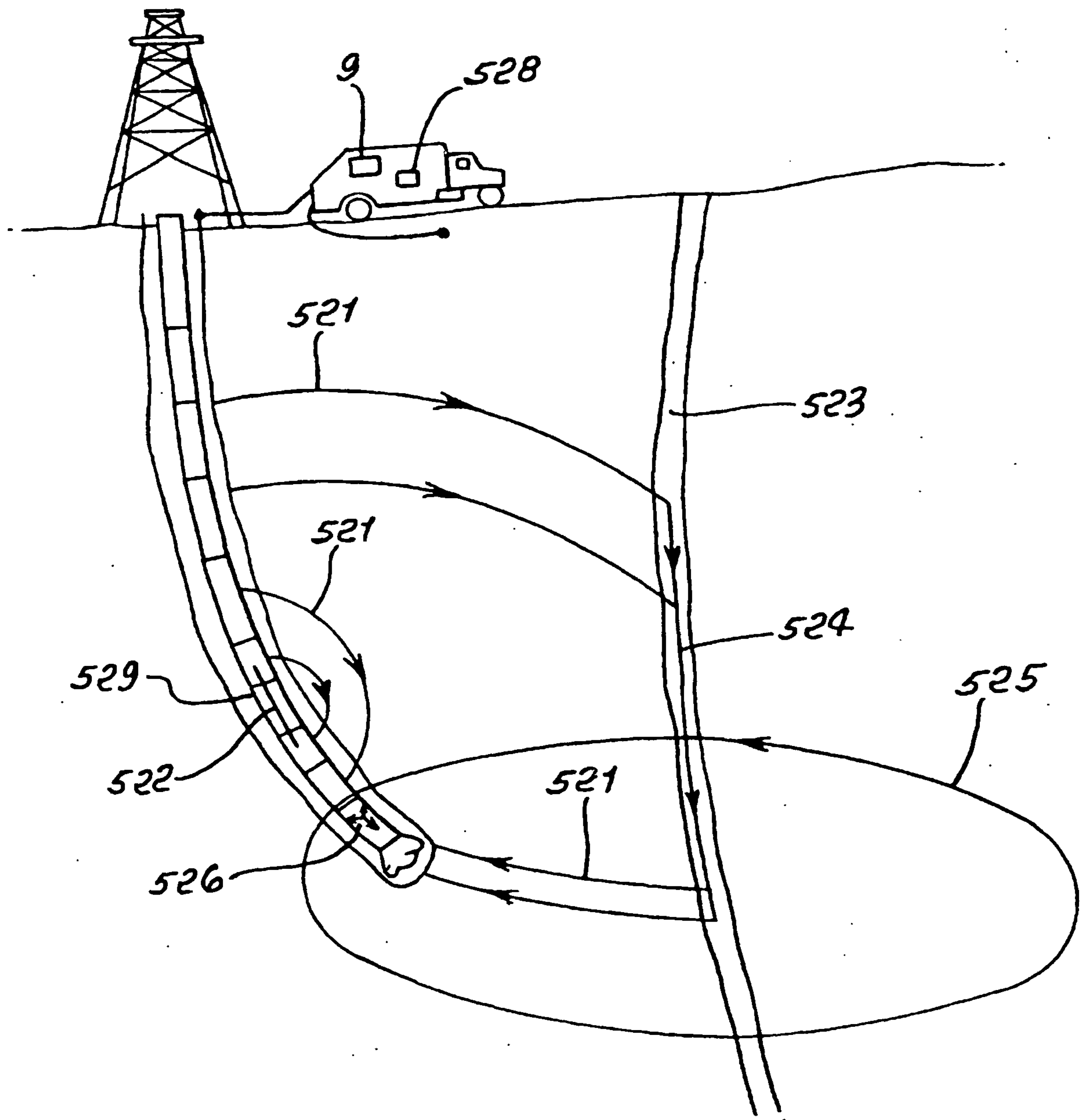
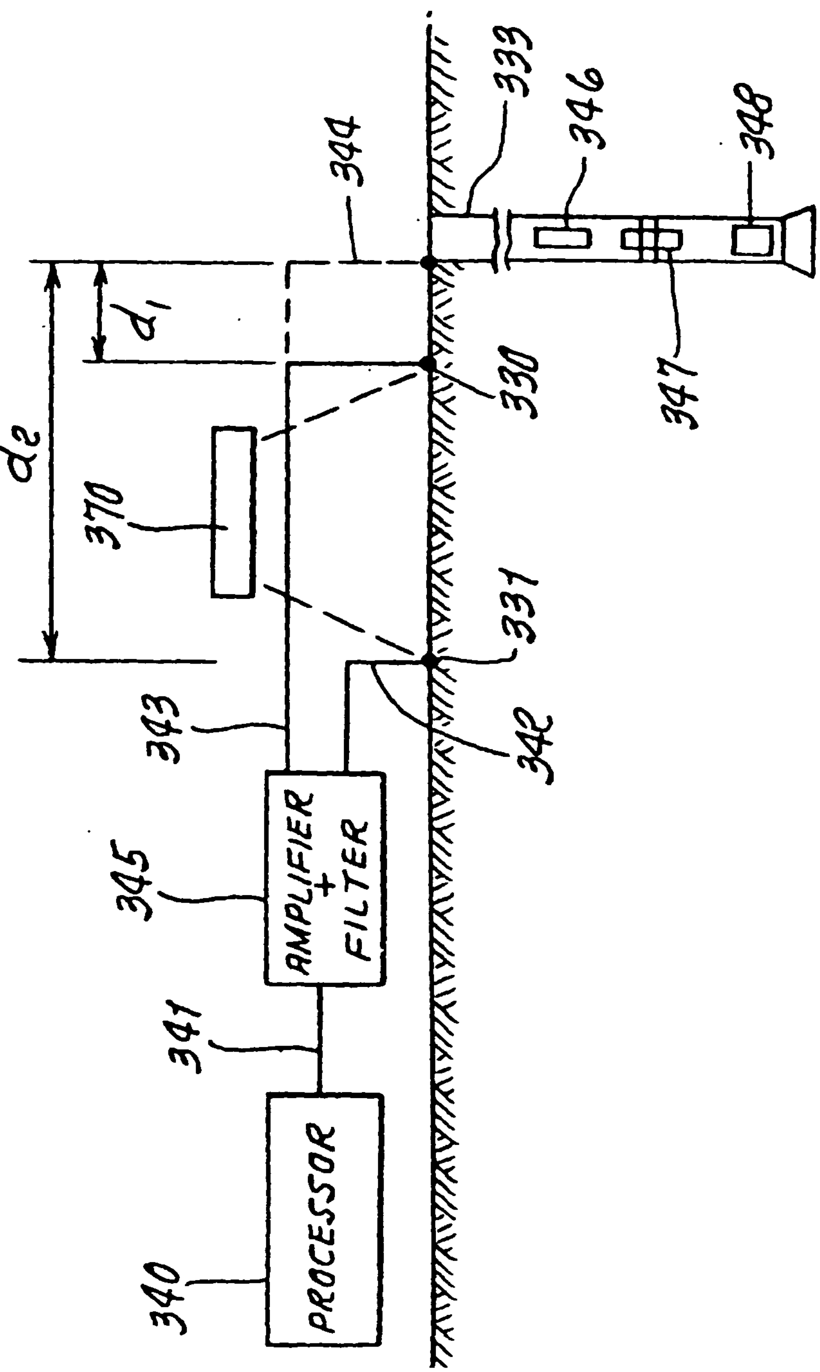


FIG. 19.

FIG. 16.





PROCESSOR
AMPLIFIER + FILTER
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d_1
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FIG. 18.

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